STRUCTURE, EARTHWORMS AND

M.J. Shipitalo

United States Department of Agriculture-Agricultural Research Service (USDA-ARS), Coshocton, Ohio, U.S.A.

INTRODUCTION

Earthworms are almost universally regarded by farmers and gardeners as a sign of healthy soil. Articles in farmer-oriented publications frequently include testimonials of how changes in crop and soil management result in the return of earthworms to fields where they were previously absent. The recent publication of the *Soil Biology Primer* and the proliferation of websites devoted to earthworms are further recognition of the perceived role of earthworms and other soil fauna in maintaining healthy soils (Table 1). From a scientific viewpoint, however, it is uncertain how much earthworms contribute to soil quality or if they are a consequence or cause of good soil health. Obviously, there are healthy soils that don't have earthworms.

Earthworms affect a number of soil processes including nutrient and carbon cycling, plant growth, and the activity and distribution of microorganisms. Perhaps the most noticeable impact of earthworms, however, is their effect on soil structure. Earthworms burrow into and ingest soil and in doing so modify soil porosity, aggregate size, and aggregate stability. The amount of soil ingested is highly dependent on the size, composition, and activity of the earthworm population and is hard to accurately measure because below-ground activity is difficult to monitor. Nevertheless, estimated ingestion rates for temperate-region soils are as high as 100 Mg ha^{-1} yr^{-1}. In tropical areas, where climatic conditions are less likely to inhibit activity, ingestion rates as high as 2600 Mg ha^{-1} yr^{-1} have been reported (1). Similarly, the contributions of earthworms to soil porosity and aggregation and the benefits of earthworm-enhanced soil structure to plant growth (2), and effects on water quality are difficult to quantify (1, 3).

TYPES OF EARTHWORMS

Part of the problem in determining the effects of earthworms on soil structure comes from incomplete knowledge of their behavior. Worldwide there are about 3000 species of earthworms (4), few of which have been investigated in detail. A number of classification schemes have been proposed that group these species based on various aspects of their behavior. The most widely used system is that of Bouché in which earthworms are divided into three groups (4, 5). *Epigeic* earthworms are generally found beneath or within accumulations of organic matter and rarely burrow into or ingest much soil (Fig. 1). Typical habitats include forest litter or manure piles, thus they have little direct effect on the structure of mineral soils. *Endogeic* earthworms burrow extensively below ground and obtain their nutrition by ingesting a mixture of soil and organic matter (Fig. 1). They form extensively branched, sub-horizontal networks of burrows in search of food, but most of their activity is in the upper 10–15 cm where organic matter levels are generally highest. Portions of their burrows are often occluded with their excrement (casts) and they occasionally cast on the soil surface. *Anecic* earthworms normally live in permanent or semi-permanent burrows that can extend deep into the soil. They feed primarily on decaying surficial organic litter that they frequently pull into their burrows or mix with excrement to form a midden (Fig. 1). The midden blocks the burrow entrance and promotes further decay of the incorporated organic residues. These categories are not absolute, however, as the behavior of many species is intermediate to these groupings and can vary with environmental conditions (5).

EFFECTS ON SOIL POROSITY

Because they burrow extensively into mineral soil, endogeic and anecic earthworms can substantially alter soil porosity. Although earthworm burrows usually account for a small fraction of the soil volume, due to their continuity, stability, and relatively large size compared to pores formed by most other mechanisms, these macropores can greatly affect movement of air, water, and solutes. A number of investigators have demonstrated that burrows made by anecic and endogeic earthworms can effectively conduct water (1, 3, 6). Because most of their activity is

Table 1 Web-based resources on earthworms and soil structure

Source	Contents	Address
USDA-NRCS Soil Biology Primer	General information on soil fauna and their effects on soil	http://www.statlab.iastate.edu/survey/SQI/SoilBiologyPrimer/index.htm
Agriculture Canada	General information on earthworms includes FAQ and numerous links	http://res2.agr.ca/london/pmrc/faq/earthwor.html
Purdue University	Extension publication on earthworms and crop management	http://www.agcom.purdue.edu/Agcom/Pubs/AY/AY-279.html
University of California	Articles on earthworm biology and sustainable agriculture	http://www.sarep.ucdavis.edu/worms
Worm Digest	Commercial publication including general articles and numerous links	http://www.wormdigest.org/

confined to surficial soil horizons, however, endogeic earthworms probably do not directly influence movement deep into the profile (7). The fact that portions of their burrows are often occluded with casts, probably further limits their effectiveness.

On the other hand, anecic earthworms have the potential to influence gas, water, and solute movement throughout the profile. For example, burrows created by *Lumbricus terrestris* L. (a widespread anecic species) are normally single, nearly vertical channels up to 12 mm in diameter and 2.4 m deep (5). These burrows can have several entrances directly underneath the midden, but these usually coalesce into a single channel within the upper few cm of soil (Fig. 1). Although the midden would seem to inhibit entry of water, field studies conducted on burrows with

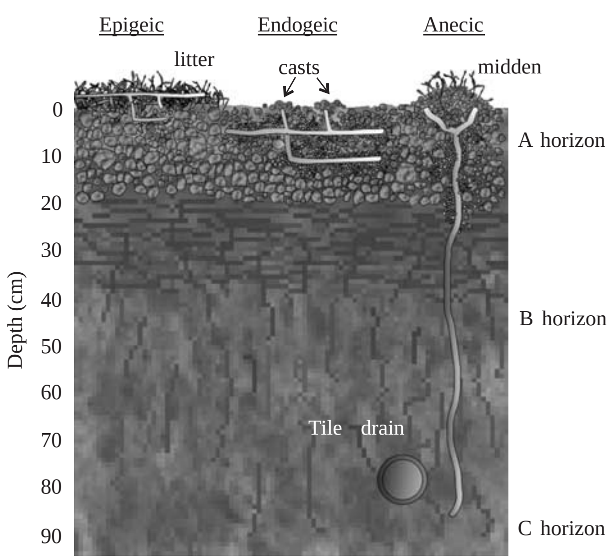

Fig. 1 Diagrammatic representation of the burrows made by the three ecological groups of earthworms as defined by Bouché.

undisturbed entrances indicate that they can transmit substantial amounts of water, up to 10% of rainfall (3, 8).

Both burrow types can increase infiltration thereby increasing plant available water and reducing surface runoff. For instance, when earthworms were eliminated from a pasture, a three-fold reduction in infiltration rate and a two-fold increase in runoff were noted (9). In cultivated soils earthworms can also reduce runoff by disrupting surface crusts that impede infiltration (10). The contribution of earthworm burrows to infiltration, however, is dependent on a number of factors. High intensity rainfall and dry soil can increase flow in earthworm burrows (3, 6, 8). Although it seems logical to assume that earthworms might block flow in their burrows, infiltration rates for burrows with the worm removed are similar to those for occupied burrows (11). In fact, occupied burrows are probably more effective in transmitting water than abandoned burrows because they are more likely to maintain near-surface continuity. Theoretically, it should be possible to model the contribution of earthworm burrows to infiltration based on their distribution and geometrical properties. This has proved difficult as not all burrows conduct water and their dimensions are not strongly correlated to their infiltration capacity (11, 12).

In rare circumstances, increased infiltration due to earthworm burrows can have negative consequences. Earthworm burrows can contribute to non-uniform distribution of water during furrow irrigation, loss of water through unlined irrigation ditches (7), and leakage of manure storage lagoons (13). Anecic earthworms can burrow close to tile lines (Figs. 1 and 2) and may increase losses of injected animal wastes in drainage waters (12). Earthworm burrows can also increase leaching of surface-applied agrochemicals, particularly when intense storms occur shortly after application on residue-covered no-till soils (3). The potential for this to occur is greatly reduced with time and low intensity, intervening, rainfalls.

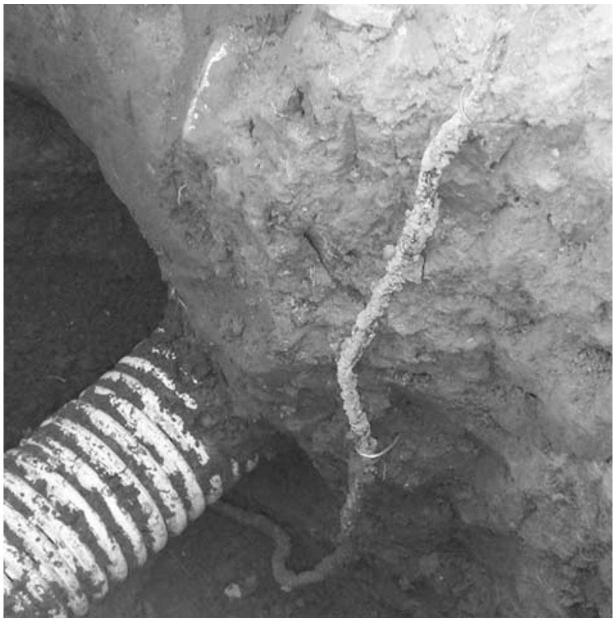

Fig. 2 This *L. terrestris* burrow, impregnated with plastic and excavated in situ, passed within 2 cm of a buried tile and had an average infiltration rate of 353 mL min^{-1}.

Ingestion of herbicide-coated residues by earthworms can also reduce leaching losses (14). Once the water enters the burrows the organic matter-rich linings may further reduce herbicide transport by increasing sorption and degradation (1).

EFFECTS ON AGGREGATION

Although earthworms feed on decaying organic matter and the microorganisms that colonize it, the material ingested by endogeic and anecic species during feeding and burrowing is predominately mineral matter (1). This mixture is excreted as casts on the soil surface or below ground, depending of the species of earthworm, location of the food source, and soil bulk density (15). The casts usually contain more clay and less sand than the surrounding soil due to selective ingestion with the effect more prominent with endogeic species, which tend to be smaller than anecic earthworms (1). Moreover, earthworm casts are usually higher in pH, contain more available nutrients, and have higher levels of microbial activity than the uningested soil (4, 5).

Freshly excreted casts are initially less water stable than uningested soil because digestive secretions and the peristaltic action of the earthworm gut disrupt many of the existing interparticle bonds. During passage through the earthworm, however, the mineral matter is intimately mixed with ingested organic matter. If casts are allowed to age or dry before being subjected to disruption their stability can exceed that of the uningested soil, thereby enhancing formation of a desirable, water-stable, granular, soil structure (1).

A number of mechanisms can contribute to the increased stability of earthworm casts with aging or drying. These include chemical or mechanical stabilization by: 1) internal secretions of earthworms, 2) plant fibers incorporated into casts, 3) growth of fungal hyphae, 4) bacterially produced gums, 5) bonding by calcium humate or mucilage, 6) wetting and drying cycles, and 7) age-hardening/thixotropic effects combined with organic bonding (1). The mechanisms are not mutually exclusive and the relative contribution of a particular process is probably dependent on a number of factors. For the most part, however, incorporation of organic matter into casts is critical either as bonding agent or as promoter of microbial activity that leads to the production of bonding agents. For this reason a positive correlation between organic carbon content and cast stability is frequently noted. Thus, casts of earthworms that have higher organic matter ingestion rates are more stable than those that ingest more mineral-rich mixtures. Additionally, the distribution of the organic bonding agents is probably more important than the total amount of organic matter within the casts (1).

Because freshly deposited casts are initially of low stability, they are subject to dispersion and transport if not protected from raindrop impact or the action of flowing water. Thus, earthworm activity can increase infiltration and reduce runoff while increasing losses of soil and sediment associated nutrients from pastures (9) and cultivated fields (15). Furthermore, foraging and midden building by anecic earthworms can reduce surface residue cover thus exposing more soil and casts to raindrop impact with negative consequences for soil structure (16).

CONCLUSIONS

In general, earthworm activity improves soil structure by increasing macroporosity and enhancing aggregation, which in turn can reduce runoff and sediment loss and provide a better environment for plant growth. Under some circumstances, however, increased infiltration, deposition of casts on the soil surface, and excessive residue removal can have undesirable consequences. For the most part, these problems can be minimized by adopting modified management practices.

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